Machine-Aided Design of an Air-Launched Missile Defense System

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The power of today's computers is altering design methodologies at the system level. Instead of manually comparing and contrasting a dozen or so options for configuring a system, machine aids can now quantitatively evaluate thousands of candidate configurations on the time scale of minutes. We apply a machine aid to improve the design of an air-launched missile defense system that intercepts ballistic targets during both their boost and terminal phases. First, the specific problem statement and corresponding quantitative formulation are defined. The discussion then moves on to the overall procedure executed by the machine aid, followed by delving into the quantitative models employed. Calculations include those for generating interceptor and target trajectories, obtaining the fire control solution, and simulating the end game. Later sections of the paper report results as well as the analytical methods employed to elicit dominant trends. The findings point to promising directions one should pursue in order to boost the system's performance and suggestions for how the machine aid itself might usefully evolve.

I. Introduction

Design of a complex system occurs in stages. One early phase is to treat the design as a collection of key design decisions. In the world of missile design, picking a propellant and supporting propulsion system serves as an example. Since these initial decisions set the stage for subsequent more detailed decisions, they have a disproportionately large impact on a project's success in meeting cost, performance, and schedule goals.

Current practice with regard to these decisions is to set up a series of trade studies. While many variants exist (see Clausing[1] to delve into one specific approach), the general theme can be envisioned as a table. Columns represent different system design concepts and rows criteria. For each design concept, selections have been made for each design decision. A group of designers get together and run through the calculations required to arrive at scores for the various criteria. Table 1 provides a notional example. Suppose we have three system concepts for a missile defense interceptor: small-scale, mid-scale, and large-scale. As seen from the table, the concepts differ in the length of the booster stage and the overall diameter. Criteria, in this case, include how far away the interceptor's launcher can stand off from the target missile's launcher, the average miss distance or mean closest distance between the flight trajectories of the interceptor and target missile, and unit manufacturing cost.

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Table 1. Notional Example of a System Design Trade Study for an Interceptor.

			small-scale	mid-scale	large-scale
			Concept		
Design Decisions	Booster Length	(m)	3.5	4.0	4.5
	Missile Diameter	(m)	0.30	0.34	0.38
Criteria	Standoff Range	(km)	260	310	350
	Miss Distance	(m)	100	3.5	0.1
	Cost	($M)	1.2	1.5	2.0

A limitation of this traditional approach is the small number of system concepts that are evaluated. Typically, the study does not evaluate all permutations of options for the design decisions. The simplified example in Table 1, for instance, does not look at an interceptor with a 4.0-m boost length and 0.30-m overall diameter. Real system trade studies often have a half a dozen or so design decisions with several options for each. This leads to the number of possible system design permutations running easily into the thousands and beyond. While many pieces of the calculations required to score each design permutation (alternatively called design case) are automated, the process in its entirety is partially manual. Thus, searching a large space of design possibilities becomes intractable.

Recent inroads, however, have been made to enhance traditional trade study analysis to expand greatly the design space covered. For example, Simmons[2] explored over a thousand possible designs for shuttle-derived vehicles for heavy launch in a completely automated fashion. The key with these efforts is a comprehensive decision aid. Designers work with the decision aid to define the design decisions and the choices for each decision; they add in the calculations and link them together to enable scoring against the criteria of interest. Once accomplished, the trade study is kicked off with results tabulated and displays generated in under an hour's time. Not only can thousands of possibilities be examined, but also turnaround times on rerunning the trade study under different assumptions typically take less than a day. For example, suppose our trade study in Table 1 assumed a certain flight trajectory for the target missile. If one wanted to run against a different trajectory, perhaps a more lofted profile, one only needs to change a few parameters in a setup file or load in a new threat trajectory lookup table. Once done, the decision aid can be asked to run again and, within an hour's time, we have new results to publish.

This paper will examine the application of such machine-aided design to air-launched interceptor concepts for missile defense. First, we cover the scope and nature of such concepts and our trade study. Then the discussion moves on to specifying the design decisions and criteria, followed by a description of the operating scenario and other assumptions. From there, we summarize the quantitative methods used to calculate the various criteria, give results, and finish with a conclusion.

II. Problem Formulation

The Missile Defense Agency (MDA) is pursuing an air-launched missile defense system. An aircraft, such as an F-18, would carry an Infrared Search and Tracking System (IRSTS) as well as utilize its radar to find and track an oncoming missile threat. Once the decision to fire has been made and the fire control solution determined, the interceptor would be released from the plane. Once clear of the plane, the interceptor initiates boost toward the target missile. A communication link exists between the interceptor and plane to send in-flight tracking updates. To accomplish this, the plane utilizes its radar.

For communications, the interceptor has a dedicated module with a conformal antenna. It is also envisioned to have one-boost stage, an infrared seeker, and closed-loop guidance. After the booster separates, leaving just the kill vehicle (KV), and its own seeker has a lock on the target missile, the end game can begin. There, divert engines adjust the KV's trajectory to match unexpected accelerations in the target missile's motion.

The assumed concept of operation has the system conducting both boost phase intercept (BPI) and terminal phase intercept (TPI). During BPI, the aircraft flies a patrol within some vicinity of an adversary's missile launchers. Once the threat missile clears the clouds, its exhaust plume from boosting is detected by the IRSTS and radar. In TPI, the plane patrols around a friendly asset it wishes to protect.

Our analysis aimed to investigate key design decisions found across the system. To that end, we choose to look at the following areas: 1) overall sizing of the interceptor, 2) booster propulsion, 3) KV propulsion, 4) aircraft's IRSTS, and 5) interceptor's seeker. Since this study represented the first phase of our efforts and the decision was made to choose a nominal baseline design, we examined the sensitivities of the criteria to the design decisions. We employed the method to find which areas of the design and/or design decisions were influential and which were not.

The preliminary analysis presented in this paper works with unclassified data. Additionally, it does not include important changes to the concept of operations that were made in subsequent rounds. For example, during TPI, the

aircraft launched the interceptor off target track updates received from external assets. Thus, the absolute performance values attained in this study are not representative of the system envisioned by MDA. Nevertheless, this initial effort did confirm the efficacy of the machine-aided design process.

III. Design Decisions

In terms of interceptor sizing, we considered the length of the boost stage, the length of the KV, and the overall missile diameter. The simplifying assumption was made that the diameter of the boost stage and KV were the same. Through assumptions on inert mass fractions and packaging dimensions of subsystem modules such as the guidance system, these sizing decisions determined the volume remaining for the propellants. Additionally, through assumptions on various densities, these dimensional variables drove the overall of mass of the booster and KV.

Specific impulse (Isp) was the parameter representing design changes to the booster propulsion subsystem. Isp was also the choice to represent variations to KV propulsion. We assumed that changes in average thrust were directly proportional to changes in Isp, effectively leaving the propellant mass flow rate and engine burn time unchanged. Furthermore, the propellant's density did not change with Isp, being set to a fixed value.

For the infrared (IR) sensors, we settled on noise equivalent power (NEP) as the key decision in both the IRSTS and the seeker. NEP gives a measurement of the effective power of noise inherent in the detector. Thus, it gives a measure of the detector's sensitivity. Other parameters in the IR sensors' models such as pixel size, effective optics diameter, and required signal-to-noise ratio (SNR) for detection were set to baseline values and did not vary.

For each of the seven design decisions mentioned above, three options were set up: 1) a baseline value, 2) 5% greater than the baseline value, and 3) 5% less than the baseline value. With three choices for each of the seven design decisions, this led to a total of 2,187 possible design cases. The baseline design settings can be found in Table 2. Note that the design decisions are indicated with an asterisk after their name.

Table 2. Baseline Air-Launched Missile Defense System Design Parameters (Those with an Asterisk after Their Name Denote Design Decisions That Were Varied by ±5% During the Study).

			Value	Source
Sizing	Interceptor Diameter*	(m)	0.34	based on THAAD in Yingbo[3]
	Booster Length*	(m)	4.0	slight increase over THAAD in Yingbo[3]
	KV Length*	(m)	0.50	based on advanced exo-KV in Wilkening[4]
Booster Propulsion	Isp*	(s)	250	typical values in Jensen[5] & Fleeman[6]
	Thrust	(lbf)	14,000	typical values in Jensen[5] & Fleeman[6]
	Density	(lb/in^3)	0.061	typical values in Jensen[5] & Fleeman[6]
KV Propulsion	Isp*	(s)	270	based on values in Fleeman[6] & Wilkening[4]
	Thrust	(lbf)	787	based on values in Fleeman[6] & Wilkening[4]
	Density	(lb/in^3)	0.054	based on values in Fleeman[6] & Wilkening[4]
IRSTS	NEP*	(W)	7.2E-14	discussions with staff & consultants at Draper & MDA
	Pixel Size	(μm)	30	discussions with staff & consultants at Draper & MDA
	Effective Optics Diameter	(cm)	20	discussions with staff & consultants at Draper & MDA
	SNR for detection	(unitless)	3.0	discussions with staff & consultants at Draper & MDA
Seeker	NEP*	(W)	2.3E-12	discussions with staff & consultants at Draper & MDA
	Pixel Size	(μm)	20	discussions with staff & consultants at Draper & MDA
	Effective Optics Diameter	(cm)	10	discussions with staff & consultants at Draper & MDA
	SNR for detection	(unitless)	6.0	discussions with staff & consultants at Draper & MDA

IV. Criteria

We settled on a total of eight criteria. The first four were performance metrics: 1) standoff range during BPI, 2) standoff range during TPI, 2) miss distance during BPI, and 3) miss distance during TPI. Standoff range during BPI measures the maximum downrange the aircraft can stand off from the adversary's missile launcher and execute a successful intercept. Standoff range during TPI has a slightly different meaning; it measures the maximum downrange the aircraft can stand off from the friendly asset it is trying to protect. Both give a sense of the system's area of coverage. Miss distance, on the other hand, is an indicator of system effectiveness within that coverage area. Strictly speaking, it measures the closest distance between the interceptor and target missile during the engagement. When combined with the notion of a lethality radius, this miss distance can give one a sense of the probability of

kill. If the miss distance is less than the lethality radius, probability of kill can rise quickly above 50%, while the opposite is true if miss distance exceeds the radius.

The fifth criteria captured cost concerns. Specifically, it assessed the unit manufacturing cost of producing an interceptor. To take economic returns-to-scale and industrial learning curves into account, the cost of the 1,000th unit manufactured was chosen.

The last three criteria are what we term design constraints. As such, the only requirement of the constraints is that the system design meets them. If we fail to meet a constraint, the design is untenable; if we greatly exceed in meeting a constraint, it is considered no better than just barely meeting it. The constraints are: 1) interceptor length limit, 2) interceptor width limit, and 3) interceptor weight limit. Limiting values were 5.18 m, 0.3556 m, and 680 kg, respectively.

V. Operational Scenario and Other Assumptions

In order to evaluate design configurations against the criteria, one needs to specify the operational scenario and other assumptions that surround the engagement. This section provides an account of the most important ones. Table 3 provides a summary with values chosen for the various parameters.

Table 3. Parameter Settings That Define the Operational Scenario and Other Assumptions.

			Value	Source
Target Missile	# Stages	(#)	3	based on an advanced North Korean ICBM in Wilkening[4]
	Boost Time	(s)	180	based on an advanced North Korean ICBM in Wilkening[4]
	Nominal Range	(km)	14,500	based on an advanced North Korean ICBM in Wilkening[4]
	Axial Acceleration Disturbance	(g)	1	adjusted down to yield informative sensitivity results
	Normal Acceleration Disturbance	(g)	1	adjusted down to yield informative sensitivity results
Engagement	Target Angle Offset	(deg)	22.5	inferred from Wilkening[4]
	Minimum Launch Delay	(s)	5	Wilkening[4]
	Maximum Aircraft Altitude	(km)	18	discussions with staff or consultants at Draper and MDA
Other	Booster Inert Mass Ratio	(unitless)	0.2	Fleeman[6]
	KV Inert Mass Ratio	(unitless)	0.5	based on advanced exo-KV in Wilkening[4]
	Booster Inert Density	(lbs/in^3)	0.05	Fleeman[6]
	KV Inert Density	(lbs/in^3)	0.04	based on advanced exo-KV in Wilkening[4]
	IR Detection Wavelength	(μm)	4.0	Wilkening[4]
	Cloud Ceiling	(m)	7,000	Wilkening[4]
	Aerodynamic Drag Coefficient	(unitless)	0.1	Wilkening[4]

The analysis centers on a threat missile based on a projected, future incarnation of a North Korean inter-continental ballistic missile (ICBM) provided in Wilkening.[4] The missile in question has three stages, reaches burnout of its boosters in 180 s, and achieves a nominal range of 14,500 km. Due to the propellant plume, its irradiance during boost was estimated at 500 W/sr; during terminal with heat generated primarily from atmospheric reentry, the value drops to 1 W/sr.

Unexpected accelerations during boost and terminal phases were set to 1 g in both the axial and normal directions. These acceleration disturbances come into play during the end-game pursuit. In order to ensure that higher accelerations set up a more challenging end-game scenario, normal acceleration of the threat missile always turned it away from the oncoming interceptor. During boost, acceleration disturbances are expected to be much higher than 1 g. However, preliminary analysis indicated accelerations higher than 1 g would yield unsuccessful intercepts due to high miss distances. Since the purpose of the study was to establish sensitivities on the above criteria, the accelerations were lowered to 1 g where some design cases had low miss distances and others did not.

Several parameters specific to the engagement become important. The aircraft was assumed able to reach 18 km at interceptor launch. Minimum launch delay denotes the time delay between detection of the target missile by the IRSTS and radar and interceptor launch. It includes time for the pilot to assess the situation and make a launch decision. Our scenario had this parameter set at 5 s. Furthermore, we did not assume that the target missile was heading directly at the aircraft, but rather at an angle. This offset angle was set to 22.5 deg.

Some of the criteria call on us to determine the mass of the booster and KV. While the design decisions size out the missile, giving us total volume, several other pieces of information are required to deduce mass. Inert mass

ratios specify what percentage of a missile section's mass is not on account of fuel. Likewise inert densities are estimates for the average density of all components other than propellant. When combined with knowledge of a section's size and propellant density, one can use this information to back out propellant mass. Estimates for the inert mass ratio of the booster and KV were 0.2 and 0.5, respectively; inert densities stood at 0.05 and 0.04 for boost and KV, respectively.

VI. Analysis Procedure

The trade study procedure first initializes by loading in a baseline design, options for each decision variable, and parameter values that define the operational scenario and capture other assumptions. Next, a loop ensues whereby every design case is scored against the eight criteria. These results are then put into a table much like the one shown in Table 1 from which various charts and reports can be run automatically. Most of the software routines in the decision aid support the calculation of the various criteria. The next few paragraphs outline the approach taken to implement such functions.

A key subroutine determines detection range of an IR sensor. Equation (1) is the core equation. As covered in books such as Hudson,[7] it determines the range required to bring the signal power high enough such that its ratio with the inherent noise in the detector breaks through the limit needed for detection. In the equation, R_{max} is the calculated range, η_a the atmospheric extinction coefficient, I_t the target's intensity, d_o the effective optics diameter, NEP the noise equivalent power, and SNR_{min} the minimum required signal-to-noise ratio for detection.

$$R_{max} = \left[\eta_a \cdot I_t \cdot \left(\pi \cdot \left(\frac{1}{2} \cdot d_o \right)^2 \right) \cdot \frac{1}{NEP} \cdot \frac{1}{SNR_{min}} \right]^{1/2} \tag{1}$$

Another subroutine generates feasible flyout trajectories for both threat and interceptor. The calculations work off a two-dimensional (2D) model of the flyout in the vertical and downrange directions. Simplifying assumptions include a nonrotating flat earth as well as constant gravitational field. Given an initial elevation angle, altitude, and velocity vector, position can be determined as a function of flight time. During boost, the flight path angle is held equal to the launch elevation angle, engine thrust is parallel to it, and drag is fixed. Such a modeling approach results in Eq. (2) for describing motion during boost, where i is either the altitude or downrange direction, a_i the acceleration in the i direction, T_i the component of boosting thrust in the i direction, D_i the component of drag in the i direction, M0 the initial mass, mRate the mass flow rate of the propellant, t time since launch, and g_i gravity (equal to 0 in the downrange direction).

$$a_i = \frac{T_i - D_i}{M0 - mRate \cdot t} - g_i \tag{2}$$

If we assume D_i and T_i to be constant, this equation can be symbolically double integrated to arrive at a closed-form expression for position as a function of time. To arrive at an approximate value for drag, the calculations are run through once, assuming no drag. From this, an average atmospheric density and missile speed can be estimated to arrive at an approximate drag value that operates during a second iteration through the equations. During coast, the whole process is much simpler given that gravity is treated as the only form of acceleration. Initial analysis using higher fidelity simulations supported the drag term being taken out during coast due to the drastic drop in air density at the higher altitudes.

The maximum standoff range calculations in both BPI and TPI make heavy use of the flyout routines. First, the procedure tabulates the threat's trajectory. Given the altitude of intercept, we wish to determine the maximum achievable downrange that still permits an intercept. Thus, a search over elevation angle commences. For each elevation angle considered, the time needed to reach the intercept altitude, termed rise time, is computed. With that rise time, a downrange is acquired. The largest, feasible downrange found combined with the threat's distance from its launcher at time of intercept plus the intercept geometry induced by the offset angle all conspire to set the maximum distance possible between the threat's launcher and the aircraft. By feasible downrange, we mean one where the detection delay plus the minimum launch delay plus the rise time was less than the threat missile's flight time until intercept. This was put into place because if such a sum were greater, then the fire control solution demands an interceptor launch before the earliest time such a launch can happen.

Keep in mind that the whole approach rests on knowing the intercept altitude. Initial analysis searched over possible intercept altitudes and launch elevation angles. It was found that sensitivity of standoff ranges to the design

decisions could be approximately captured by only searching over elevation launch angle and holding the intercept altitude to a value optimized for the baseline design. Holding the intercept altitude fixed sped up computation time by an order of magnitude, keeping run times reasonable.

The end game performance is simulated using the 2D missile-target geometry dynamics of an accelerated target and a KV depicted in Fig. 1.[6,9] The goal of the simulation is to calculate miss distance (minimum distance between target and KV) that a KV can achieve with limited fuel and maximum thrust determined by a specific set of design parameters.

Figure 1. End-game kill vehicle-target geometry and kill vehicle guidance law.

The end-game is set to start at completion of the coasting phase after the KV's seeker engages the target. The initial states (positions and velocities: V_T and V_{KV}) of the KV and target are used to define the missile-target end-game geometry, such as the inertial coordinate systems ($\{X_T, Y_T\}$ and $\{X_{KV}, Y_{KV}\}$). The nominal target acceleration predicted plus disturbance are applied to the target dynamics in the frame of $\{X_T, Y_T\}$. The guidance law for the KV is based on the typical Proportional Navigation Guidance (PNG) law augmented with target acceleration.[8] As in Fig. 1, the PNG law produces a desired normal acceleration (A_N) perpendicular to the line-of-sight (LOS) vector. Although the PNG law implemented in the end-game is very similar to the typical one,[8] it has a couple of unique features:

1) V_C and A_{target} are assumed to be estimated by direct measurement and onboard propagation. Since the target is under significant acceleration during BPI, the measurement of these parameters is prerequisite to a successful interception within the limited fuel budget. Of course, some uncertainty is modeled into the process of measurement and estimation. The measurement is assumed to be acquired from aircraft's radar and IRSTS in concert with interceptor in-flight updates. In fact, the PNG law employs a gain-scheduling technique.

2) Normal acceleration A_N is assumed to provide the KV with significant axial acceleration as well as divert acceleration commands. These components are heuristically derived as depicted in Fig. 1. The accelerated target with significant maneuverability requires early engagement of the end-game and axial acceleration capability of the KV. Therefore, the motor is assumed to provide the KV with axial and divert acceleration. The seeker is also assumed to have an extended capability in range and field of view (FOV). The wide FOV may yield a significant axial component of A_N. This heuristic approach is believed to be a first-order approximate of an ideal guidance law that orchestrates the PNG law and Lambert guidance.

3) Coasting time to control the start of the end game is used as a parameter to trade off miss distance and fuel usage. In the case of intercepting an accelerated target, the open-loop ideal LOS vector that leads to perfect interception is typically time-varying. The typical PNG law is observed to consume fuel unnecessarily by regulating the current LOS vector to the initial reference LOS vector (λ_{ref}) and not to the open-loop ideal LOS vector. An ideal approach to mitigate this negative effect is obviously to regulate the current LOS vector to the open-loop ideal LOS vector. Instead, a heuristic way is used in this study that controls the start of the end-game via coasting time. By doing this, useless fuel consumption is greatly reduced so that the interception performance of the KV can be estimated with higher accuracy.

The cost was based on the missile's weight. Fleeman[6] presents empirical data on missile unit costs and fits an empirical curve to it. Equation (3) gives the relation, where M_I is total the mass of the interceptor and C_{unit} is the cost per unit.

$$C_{unit} = 6100 \cdot \left(M_I \right)^{0.758} \tag{3}$$

VII.   Results

Table 4 gives the range and average of scores for performance metrics and cost during TPI and BPI. As can been seen from the table, the relatively small 5% changes in values for the design decisions do have a significant impact on performance given the design baseline, operating scenario, and assumptions.

Figures 2 through 6 indicate performance sensitivities to the design decisions. Specifically, they represent a statistical way to assess the average impact a given design parameter has on a given metric. Given a chosen design
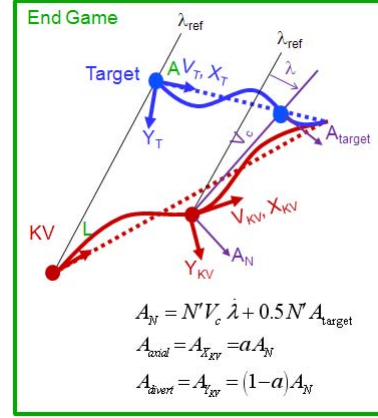
Table 4. Range and Average of Scores for Performance and Cost Metrics Over the Design Cases.

METRIC	MIN	MEAN	MAX
BPI STANDOFF RANGE [km]:	290.49	310.23	329.8
TPI STANDOFF RANGE [km]:	61.61	70.27	79.29
BPI MISS DISTANCE [m]:	0	3.5	144.22
TPI MISS DISTANCE [m]:	0	0.05	0.09
COST [$M]:	1.32	1.49	1.66

decision, all 2187 configurations are separated into three groups: 1) those with the design decision set to the "LOW" (-5%) option, 2) set to the "BASELINE" option, and 3) set to the "HIGH" (+5%) option. For each design case in the "LOW" group, its counterpart in the "BASELINE" group is found that has identical options for the remaining design decisions. This "BASELINE" counterpart is then subtracted from the "LOW" case to compute a difference for each configuration in the "LOW" group; these differences are then averaged to determine the average sensitivity value for setting the particular design decision to "LOW." The same statistics are determined for the "HIGH" group as well.

Figure 2 covers the sensitivities on standoff range during BPI. Increases in interceptor diameter and booster length have a negligible effect. Both length and diameter increases add more propellant mass, but they also add weight. Additionally, diameter increases add drag. Booster propulsion stands out as the main driver, with decreases in KV helping due to the lower payload weight that is being boosted. Figure 3 reports on standoff range during TPI, and we see the same factors come into play as seen during BPI. Additionally, the tracker's range is greatly shortened due to lower irradiance given off by the target, and the target average speed is much higher than that during boost. Thus, the time between when the target is detected and it reaches the intercept altitude is shorter than during BPI. As a result, improving the tracker gives it longer detection ranges, leaving more time for the intercept to fly out to the intercept point. Also, shortening booster length results in higher accelerations during boost, which allows the interceptor to rise to the needed intercept altitude in a shorter amount of time. Thus, longer standoff intercepts become possible because the interceptor can get to the point of intercept more quickly.
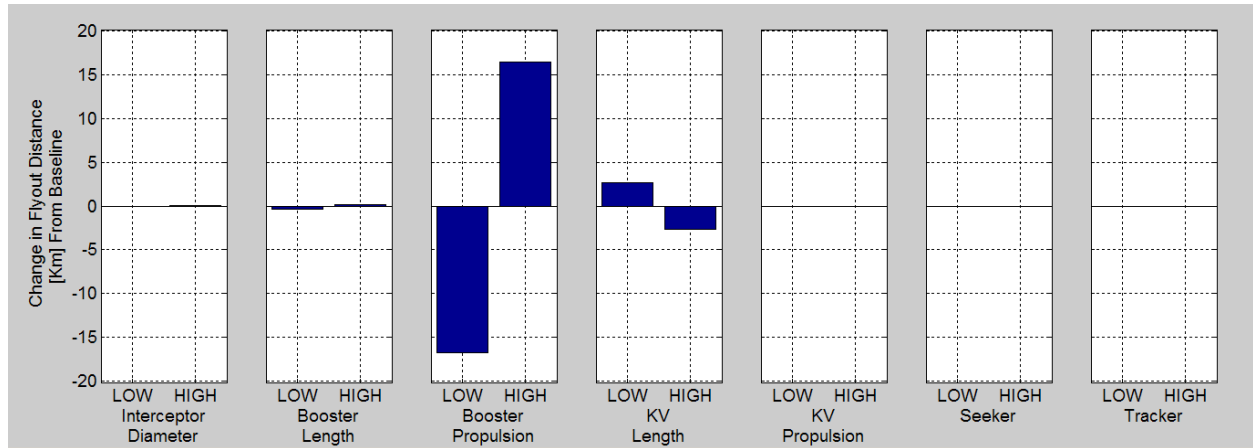

Figure 2. Sensitivity of maximum standoff range during BPI to changes in design decisions.
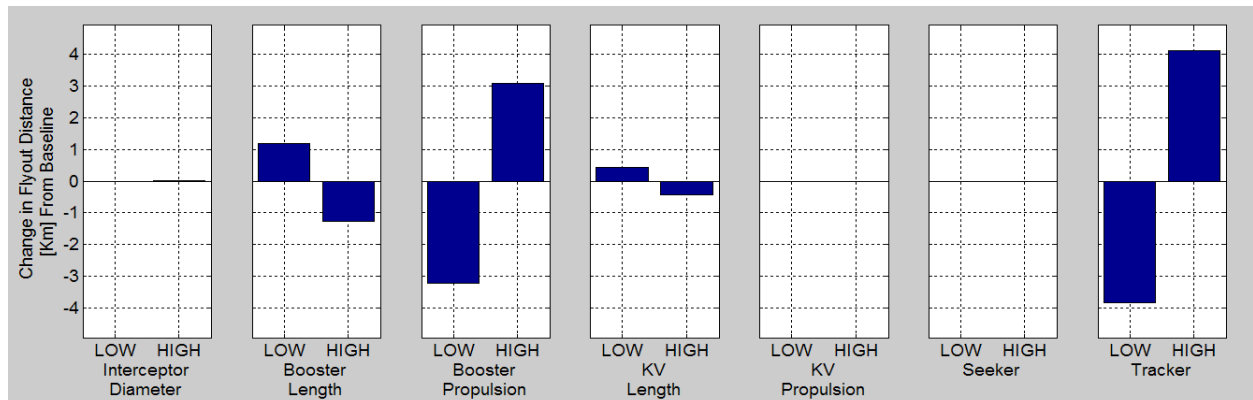

Figure 3. Sensitivity of maximum standoff range during TPI to changes in design decisions.

Miss distance during BPI, as shown in Fig. 4 is rightly influenced by changes to the KV. Specifically, a large diameter and KV length allows for more propellant mass for divert, and better propulsion increases the efficient conversion of that mass into thrust. Increases in booster length and propulsion affect the initial velocities of the end game. A smaller length and larger Isp put the interceptor at a higher velocity at the start of the end game. Initially, this causes the interceptor's guidance to think it is overshooting the target; the proportional guidance law overcorrects, inefficiently using propellant by doing so. In some cases, this causes the KV to run out of divert fuel before the intercept.
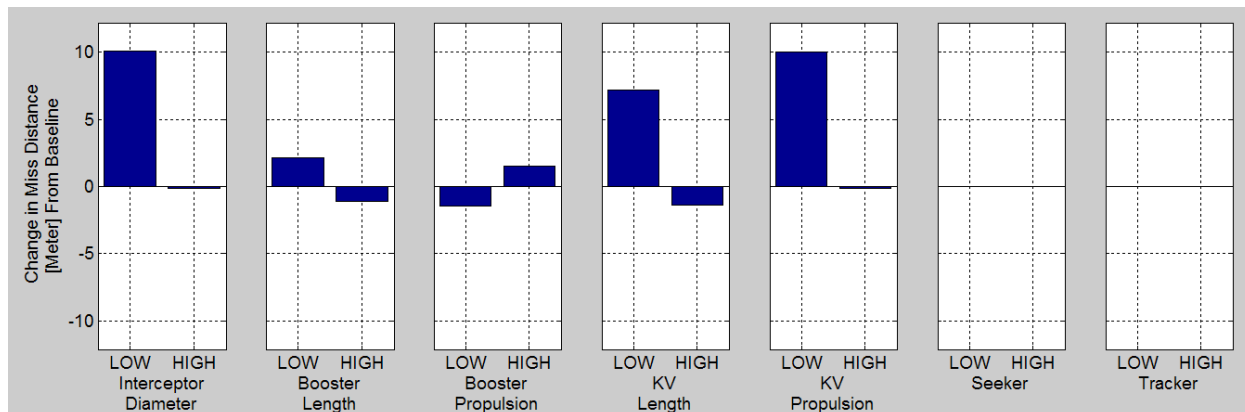

Figure 4. Sensitivity of miss distance during BPI to changes in design decisions.

Miss distance TPI is a very different story as can been seen in Fig. 5. Here, the target's nominal acceleration profile is only driven by gravity. The overall acceleration profile is thus less challenging than boost, and the guidance routine has enough acceleration capability and propellant mass to handle the disturbances.
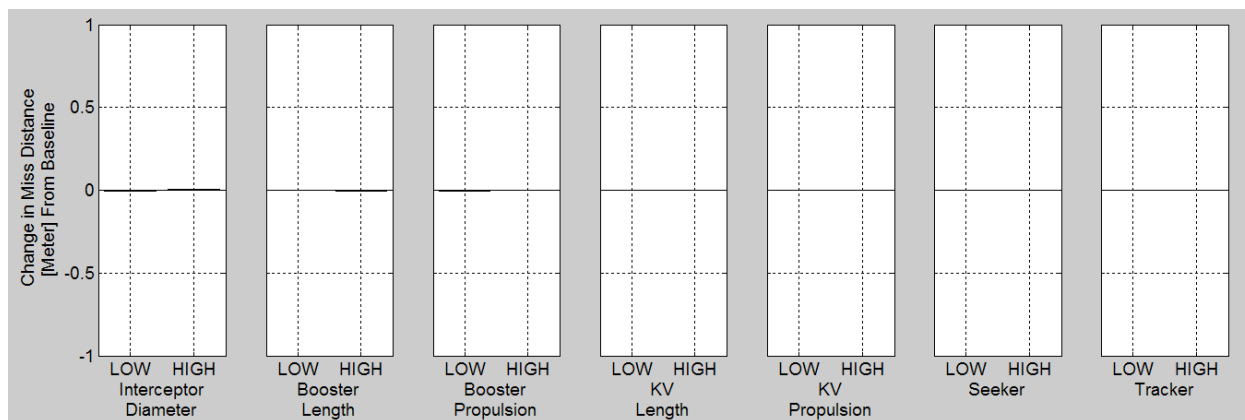

Figure 5. Sensitivity of miss distance during TPI to changes in design decisions.

Cost results in Fig. 6 are as expected. Diameter drives up weight by the square and has the largest impact. The bar charts show that even small changes in weight can increase costs significantly.

Once all cases have been scored, we can search through the cases to find those that meet a desired set of performance limits. Suppose we wish to meet all design constraints, keep miss distance below 0.5 m, BPI standoff range above 300 km, TPI standoff range above 75 km, and cost less than $1.35 million. The list of feasible design cases is illustrated in Table 5, with the most promising one highlighted. As the table shows, bumping up KV propulsion pushes the miss distance to acceptable levels. Standoff is kept high via high boost propulsion. Sizing is kept small to keep costs down. Changes to the seeker are irrelevant (denoted by the "ANY" term). During boost, the plume burns so bright that sensitivity is not a limiting factor. A better IRSTS does matter, however, permitting early detection of the target missile, leaving more time for the interceptor to fly out to its intercept point.
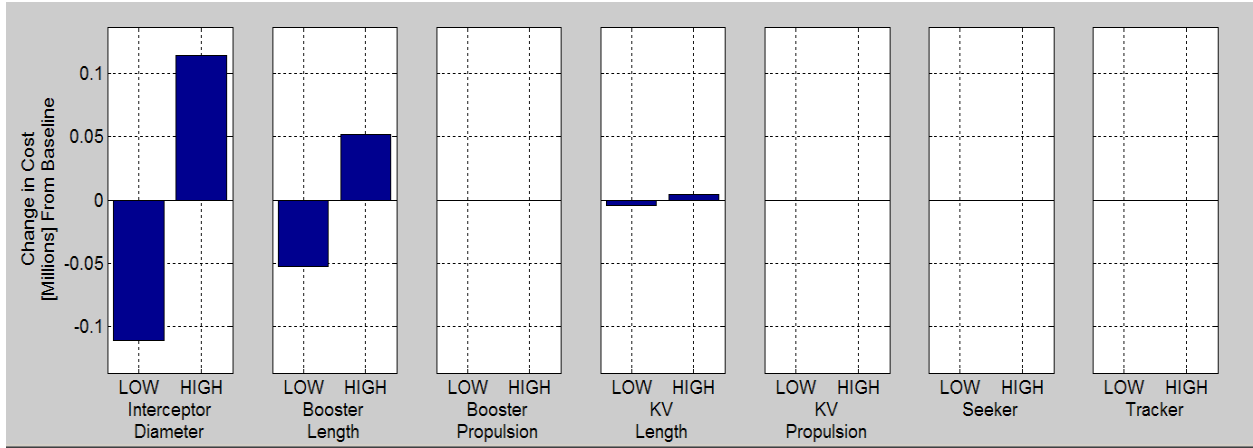
Figure 6. Sensitivity of cost to changes in design decisions.

Table 5. List of Feasible Design Cases with Promising Case Highlighted.

CASE	boost miss [m]:	boost standoff [km]:	terminal miss [m]:	terminal standoff [km]:	cost [$M]:	Diameter	Boost Length	Booster Propulsion	KV Length	KV Propulsion	Seeker	Tracker
1589	0.02	309.94	0.07	75.5	1.33	LOW	LOW	BASE	BASE	BASE	ANY	HIGH
1632	0.04	309.94	0.07	75.5	1.33	LOW	LOW	BASE	BASE	HIGH	ANY	HIGH
1868	0.04	307.18	0.07	75.06	1.33	LOW	LOW	BASE	HIGH	BASE	ANY	HIGH
1908	0.04	307.18	0.07	75.06	1.33	LOW	LOW	BASE	HIGH	HIGH	ANY	HIGH
1828	0.04	312.75	0.04	76.01	1.32	LOW	LOW	BASE	LOW	HIGH	ANY	HIGH
469	0	326.35	0.07	78.81	1.33	LOW	LOW	HIGH	BASE	BASE	ANY	HIGH
537	0.06	326.35	0.07	78.81	1.33	LOW	LOW	HIGH	BASE	HIGH	ANY	HIGH
838	0.04	323.56	0.05	78.31	1.33	LOW	LOW	HIGH	HIGH	BASE	ANY	HIGH
921	0.04	323.56	0.05	78.31	1.33	LOW	LOW	HIGH	HIGH	HIGH	ANY	HIGH
713	0.04	329.17	0.09	75.04	1.32	LOW	LOW	HIGH	LOW	HIGH	ANY	BASE
725	0.04	329.17	0.07	79.25	1.32	LOW	LOW	HIGH	LOW	HIGH	ANY	HIGH

VIII. Conclusions

This paper has outlined a machine-aided method for conducting a trade study at the system design level. It allows the designer to set up a baseline and options for the design decisions as well as to specify an operating scenario and other assumptions all through a set of parameter files. Once done, the trade study can be kicked off and results obtained in under an hour on a desktop PC. The machine-aid works well with the iterative process of design. Results can be generated and top design configurations listed to give the designer insight into the system design space. After such a search, the designer can rerun the trade study with changes to the parameter files. Between the designer's guidance and the computer's number crunching capability, the process can survey a vast number of possibilities to attempt to arrive at the proverbial sweet spots in the design space.

At least two promising paths forward exist. The current effort enumerated all possible design cases. More extensive investigations may have a dozen or so design decisions with upwards of ten options for each. At this point, the number of design options gets into the trillions. To make the process tractable, we could abandon full enumeration and embrace an efficient search of the design space assisted by statistical sampling. Genetic algorithms and its variants promise a way to implement this strategy. At the same time, since the evaluation of design cases are not always dependent on each other, many such evaluations can be done in parallel. This opens the door for use of parallel computation, particularly grid computing.   Taken together, efficient search techniques and parallel computation promise to vastly expand the system design space one can explore.

IX. References

[1]Clausing, D.P., *Total Quality Development: A Step-By-Step Guide to World Class Concurrent Engineering*, ASME, New York, NY, March 1994.

[2]Simmons, W.L., Koo, B.H.Y., Crawley, E.F, "Space Systems Architecting Using Meta-Languages," Proceedings of 56th International Astronautical Congress 2005, Fukuoka, Japan, October 2005, IAC-05-D1.P03.

[3]Yingbo, H., Yong, G., "THAAD-Like High Altitude Theater Missile Defense: Strategic Defense Capability and Certain Countermeasures Analysis," *Science and Global Security*, 11:151-202, Taylor & Francis Inc., 2003.

[4]Wilkening, D.A., "Airborne Boost-Phase Ballistic Missile Defense," *Science and Global Security*, 12: 1-67, Taylor & Francis Inc., 2004.

[5]Jensen, G.E., Netzer, D.W., *Tactical Missile Propulsion*, AIAA, October 1996.

[6]Fleeman, E.L., *Tactical Missile Design*, AIAA, 2001.

[7]Hudson, R.D., *Infrared System Engineering*, Wiley-Interscience, January 1969.

[8]Zarchan, P., *Tactical and Strategic Missile Guidance Second Edition,* AIAA Progress in Astronautics and Aeronautics, Vol. 157, Washington DC, 1994.

[9]Fleeman, E.L., "Methodology for Predicting Miss Distance for Air Launched Missile," AIAA-82-0364, AIAA Aerospace Sciences Meeting, 1982.